Model Checking of Workflow Schemas

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Abstract

Practical experience indicates that the definition of real-world workflow applications is a complex and error-prone process. Existing workflow management systems provide the means, in the best case, for very primitive syntactic verification, which is not enough to guarantee the overall correctness and robustness of workflow applications. The paper presents an approach for formal verification of workflow schemas (definitions). Workflow behaviour is modelled by means of an automata-based method, which facilitates exhaustive compositional reachability analysis. The workflow behaviour can then be analysed and checked for safety and liveness properties. The model generation and the analysis procedure are governed by well-defined rules that can be fully automated. Therefore, the approach is accessible by designers who are not experts in formal methods.

1. Introduction

Workflow Management Systems provide automated support for defining and controlling various activities (tasks) associated with business processes [1, 2]. A Workflow Schema is used to represent the structure of an application in terms of tasks as well as temporal and data dependencies between tasks. A Workflow Application (or just Workflow) is executed by instantiating the corresponding workflow schema [3].

The aim of providing automated support for business processes is to reduce costs and flow times, to improve the robustness of the process and to increase productivity and quality of service [4, 5]. However, specifying a real-world workflow schema is a complex manual process, which is prone to errors. Incorrectly specified workflow schemas result in erroneous workflow applications, which, in turn, may cause problems in the organisation where they are deployed. It is crucial to be able to verify the correctness of a workflow schema before it becomes operational.

Many commercial workflow management systems provide the means for some basic syntactic verification, while a workflow schema is designed. They check, for example, for the existence of inputs and outputs in task specifications. However, more thorough and rigorous analysis is required to ensure that the schema is correct [6, 7]. For instance, we need to be able to check that the workflow eventually terminates, that there are no potential deadlocks, or that a certain path of execution is possible.

Within the C3DS ESPRIT project, we address this issue by integrating a workflow definition language with a model checking method. The two methods were developed by project partners, have been used extensively, and are supported by powerful automated tools. The workflow definition language has been recently incorporated in a proposal for OMG's "UML Profile for EDOC" RFP [8, 9]. The TRACTA model-checking approach follows a compositional approach to exhaustive reachability analysis, which has proved to scale well in real-world applications. Analysis is performed in a fully automated way with the LTSA toolkit [10]. Integration of the two involves a mapping of the features of the workflow definition language with features of FSP, the specification language of LTSA. The mapping is governed by well-defined rules, which allow for translations to be performed in an automatic way. The FSP model extracted can be used for checking both safety and liveness properties. Generic properties of workflow schemas can be provided to users as predefined options. Moreover, for users that are familiar with model checking, the LTSA offers the flexibility of defining additional (application-specific) properties, which can also be automatically checked.

The remainder of this paper is organised as follows. Section 2 provides an overview of the semantics of our workflow definition notation, outlines the requirements for verification in this context and introduces the TRACTA approach. Sections 3 and 4 form the core of the paper. Section 3 proposes a complete mapping of all workflow schema elements to LTSs. Section 4 discusses the classes of safety properties that can be verified using the TRACTA techniques and the LTSA toolkit. In both sections, the theoretical concepts are illustrated by means of a simple example: a workflow managing travel arrangements. The

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paper is concluded (section 5) with a critical discussion of the presented approach and directions of future work.

2. Background

2.1. Defining Workflow Schemas

A workflow schema represents the structure of a business process as a collection of tasks and their dependencies. A task is an application-specific unit of activity. There can be two types of dependencies between tasks: 1) *notification* dependencies indicating temporal (causal) relations; 2) *dataflow* dependencies indicating that a task requires some input (data) from another task. In the following, we present the principles of our notation for workflow schema definition [11, 12].

A task can start in one of several initial states and can terminate in one of several output states. Thus, a task is modelled as having a set of *input sets* and a set of *output sets*. Each such set consists of a (possibly empty) set of data objects. In Figure 1, task t_3 is represented as having three input sets I_1, I_2, and I_3, and two output sets O_1 and O_2.

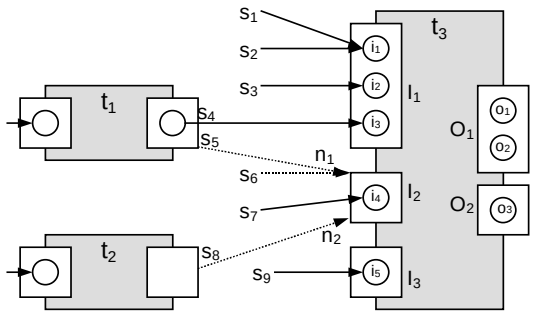


Figure 1. A workflow schema defining inter-task dependencies.

The execution of a task is triggered by the availability of an input set; only the first available input set will trigger the task. For an input set to be available, *all* its dataflow and notification dependencies must be satisfied. For example, in Figure 1, input set I_1 of task t_3 requires three dependencies to be satisfied: objects i_1, i_2 and i_3 must become available (dataflow dependencies). On the other hand, input set I_2 requires three dependencies to be satisfied: object i_4 must become available and two notifications, n_1 and n_2, must be signalled (notifications are modelled as data-less input objects). All these dependencies (data and notification) are logically AND'ed for an input set to be available. A given input can be obtained from more than one source (e.g., two for object i_1 in set I_1 of task t_3), a logical OR of sources. If multiple input sources become available simultaneously, then one source is selected deterministically by the execution environment.

The data dependencies of an input or output set are represented by the data objects of that set. They are therefore part of the definition of the task that contains the set. On the other hand, notifications are causal dependencies that depend on the context a task is instantiated in. The number of incoming notifications of a set (that are logically AND'ed with its data objects) and the alternative sources of each of them (logically OR'ed inputs) are defined when a task is interconnected with other tasks in some context.

To allow workflow applications to be designed in a hierarchical way, tasks can be *composite*: collections of instances of other, inter-dependent tasks. Therefore a task can be either primitive (implemented by some application service) or composite (consists of other primitive or composite tasks). Figure 2 illustrates an example of a composite task called `TripOrganiser`. The task provides the schema definition for a workflow that makes trip arrangements.

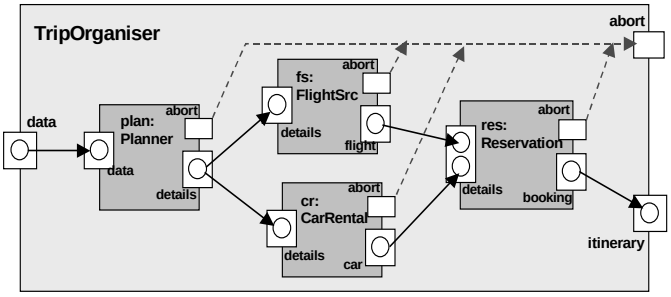


Figure 2. An example of workflow schema.

2.2. Requirements for workflow verification

Our experience with building large workflow systems indicates that it is important for the designer to be able to apply a rigorous verification method on the workflow schema and argue formally about the correctness of the resulting workflow applications. In this context, we have identified a number of requirements to be satisfied by any such verification method:

1. Have a solid mathematical foundation and allow for rigorous and formal analysis of both safety and liveness properties.
2. Perform exhaustive analysis at design-time (of the workflow schema) as well as interactive simulation of the workflow model.
3. Employ algorithms that are computationally efficient in order to be applicable to real-world systems. These algorithms should be supported by automated tools.
4. Follow a compositional approach in order to enable incremental analysis while the system is designed and to support re-use of specifications in multiple contexts.
5. Generate meaningful diagnostic information, in the form of execution traces, to indicate potential errors to the designer.

6. Use a comprehensible graphical representation for humans and also an equivalent well-defined and space-efficient formal notation for usage with the tools.
7. Be understandable and accessible by users who have no special expertise in the area of modelling and formal methods.

2.3. The TRACTA approach

The TRACTA approach has been extensively used for modelling and analysing concurrent and distributed systems [13, 14]. It is based on the use of *Labelled Transition Systems* (LTS) for modelling the behaviour of system components and for expressing system properties.

In order to integrate analysis with other activities of software development, TRACTA uses a compositional approach to modelling, by following the phases of hierarchical system design. Behaviour is attached to the software architecture by specifying a labelled transition system for each primitive component in the hierarchy (primitive is a system component which cannot be expanded to sub-components, at least for the sake of analysis). Following the terminology of traditional process algebras, the LTS of a primitive component is equivalent to a finite-state interacting process. An LTS contains all the reachable *states* and executable transitions (triggered by *actions*) of a process. The behaviour of composite system components is defined as the composition of the LTSs of their constituent components.

TRACTA exhaustively explores the reachable states of an LTS, a technique known as *reachability analysis*. The main disadvantage of this technique is state explosion. That is, the exponential relation between the system state-space and the number of its constituent components. TRACTA takes advantage of the hierarchical structure of the system in order to address this problem. As the system behaviour is composed in a bottom-up manner, internal details (actions) of a subsystem's behaviour are hidden and the subsystem is minimised, at intermediate stages of the analysis. In general, only a subset of the actions in a subsystem's LTS are of interest to external systems (processes) that have to interact with it.

Explicit representation of LTSs becomes impractical for systems with more that a few states. For this reason, TRACTA uses a simple process algebra notation called FSP (stands for *Finite State Process*) to specify the behaviour of components in a system [10]. FSP is not a different way of modelling a system. It is a specification language with well-defined semantics in terms of LTSs, which provides a concise way for describing LTSs. Each FSP expression can be mapped onto a finite LTS and vice versa.

TRACTA is supported by the *LTSA* software toolkit, which provides for automatic composition, analysis, minimisation, animation and graphical display of system models expressed in FSP.

Primitive system components

Primitive system components are defined as finite-state processes in FSP using action prefix "`->`", choice "`|`" and recursion. If `x` is an action and `P` a process, then `(x->P)` describes a process that initially engages in the action `x` and then behaves exactly as described in `P`. If `x` and `y` are actions, then `(x->P|y->Q)` describes a process which initially engages in either of the actions `x` or `y`, and the subsequent behaviour is described by `P` or `Q`, respectively. The definition of a primitive component may use an *auxiliary* process (used as a means for modular FSP specifications).

FSP uses an *interface* operator '`@`', which specifies (using prefix matching) the set of action labels which are visible at the interface of the component and thus may be shared (synchronisation points – used for interaction) with other components. All other actions are "hidden" and will appear as silent "τ" (tau) actions during analysis, if they do not disappear during minimisation of the component. When it is more concise to describe what actions are hidden rather than which actions remain observable, the *hiding* operator "\" may be used instead.

Composite system components

Composite-component processes are defined in terms of other, non-auxiliary processes. Their identifiers are prefixed with "`||`". The process of a composite component does not define additional behaviour; it is simply obtained as the parallel composition of instances of the processes it is made of. Process instances are denoted as "*instance-name:type-name*". The LTS of the instance is identical to that of the type, with action labels prefixed with the instance name. The instance name is not necessary if there is just one instance of a process in a given context. Composition expressions use parallel composition (`||`) together with operators such as re-labelling (`/`), action hiding (`\`) or interface (`@`). Communication occurs when interfaces are bound together. It is modelled by means of synchronisation of shared actions (the remaining actions are interleaved). Actions that correspond to bound interfaces are re-labelled to a common name in order to be synchronised when behaviours are composed. Re-label specifications are of the form "*new-label/old-label*".

More details of the TRACTA approach and the FSP specification language will become clear during the discussion of workflow modelling and analysis, in the following sections.

3. Workflow modelling

The model of each workflow schema consists of two parts. A generic part, which models elements that are common to every schema, such as input/output interfaces and dataflow/notification dependencies between tasks. An application-specific part, which models the actual tasks in

the schema and their inter-dependencies. In the rest of this section, the models are presented in the form of FSP specifications and, when appropriate, as LTS diagrams produced by the LTSA tool.

3.1. Task interfaces

A task interacts with its environment through its *interface sets*. Interface sets consist of zero or more data *objects* (representing dataflow dependencies) and inbound and outbound *notifications* (representing notification dependencies). Interface sets model the common behaviour of input and output sets of tasks.

- *An interface set is "available", if all its dataflow and notification dependencies are satisfied. When an interface set is available, then all of its constituent objects and outbound notifications are also available.*

An interface set is modelled as the parallel composition of a set of objects and inbound and outbound notifications.

An interface object can perform `input` and `output` actions, reflecting the fact that the object receives and outputs data, respectively. An interface becomes available when *all* its constituent objects are available (a logical AND operation). To enforce this, all objects in a set need to synchronise on a common action `available`. An object can only perform `available` after performing action `input`. Therefore, the behaviour of an object with identification `ID` (to uniquely identify it in the set) is modelled as follows:

```
Object (ID=1) = (input[ID] -> available
                    -> output[ID] -> STOP).
```

Action `available` is also used to make sure that all inbound notifications are received before an interface set becomes available and also, that outbound notifications are provided only after the interface set becomes available:

```
InNotification (ID=1) =
      (inNotify[ID] -> available -> STOP).
OutNotification =
      (available -> outNotify -> STOP).
```

An interface produces at most one outbound notification (which can be bound to more than one task). Thus, no identifier is required for this type of notifications. A process `Iface_Problem` is introduced to model a transition to an error state, if an interface instance is specified with more than one outbound notification. If an interface set does not contain any objects and has no notification dependencies, it is unconditionally available, as modelled by process `Default`.

```
Iface_Problem = (erroneous -> ERROR).
Default = (available -> STOP).

|| Iface (Objs=1, INotfs=1, ONotfs=1) =
   if (ONotfs >= 2) then
        Iface_Problem
   else (if (Objs > 0) then
      (forall [i:1..Objs] Object(i))
        || if (INotfs > 0) then
           (forall [i:1..INotfs]
              InNotification(i))
        || if (ONotfs > 0) then
          OutNotification
        || if (Objs==0 && INotfs==0
                 && ONotfs==0) then
             Default ).
```

Figure 3 illustrates the LTS of an interface with one object, one inbound and one outbound notification. The interface becomes available only after both `inNotify.1` and `input.1` have been performed (in any order). Following action `available`, actions `output.1` and `outNotify` can also be performed.

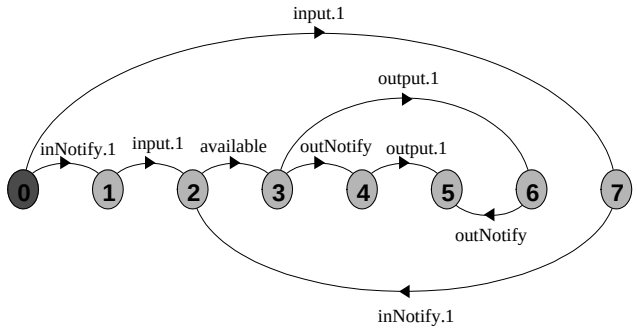


Figure 3: LTS of an interface set, with one object, one in- and one out- notification.

3.2. Primitive tasks

The main entities of a primitive task that need to be modelled are its interfaces, qualified as *input* and *output sets*. They are modelled as interfaces that have zero notifications. A task's notification dependencies are context dependent. In the general case, a task may be instantiated in more than one context. Therefore, in our model, notifications are added when a task is introduced in a context (composite task).

```
minimal
|| AbsInputSet (Objs=1) =
   (Iface(Objs, 0, 0)) @ {available, input}.

minimal
|| AbsOutputSet (Objs=1) =
   (Iface(Objs, 0, 0)) @ {available, output}.
```

Information that is concerned with the outputs of input sets and the inputs of output sets is encapsulated within the model of primitive tasks. The only actions kept explicitly visible are the ones prefixed with labels `input` and `available` for input sets, and `output` and `available` for output sets. The prefix `minimal` is added to the processes to make sure that, during the generation of the model, our tools will not only hide the actions that are not made visible, but will also minimise the corresponding LTSs. The advantage of minimisation is that it results in a more compact but behaviourally equivalent model.

A primitive task's behaviour is dictated by two rules:

- *The execution of a task starts as soon as one of its input sets is available.*
- *When the execution of a task completes, exactly one of its output sets is available.*

The two rules also capture the causal dependency between a task's input and output sets. This behaviour pattern is common to all primitive tasks and is modelled by the process `AbsTaskImpl`. This process also models the fact that, even if more than one input set is available, just one is selected by the internal task behaviour and exactly one output is produced.

```
AbsTaskImpl (InSets=1, OutSets=1) =
  (in_ready[i:1..InSets] -> Execute),
Execute = (out_ready[o:1..OutSets] -> STOP).
```

A specific primitive task is then defined as the parallel composition of instances of its input and output sets with an instance of the above default implementation process. For example, the primitive task `Planner` of Figure 2 is modelled as shown below. The renaming reflects the bindings of the task's interfaces to `AbsTaskImpl`.

```
|| Planner = (   AbsTaskImpl(1, 2)
         || data:AbsInputSet(1)
         || abort:AbsOutputSet(0)
         || details:AbsOutputSet(2)
         )
      / { data.available/in_ready[1],
          abort.available/out_ready[1],
          details.available/out_ready[2] }.
```

3.3. Composite tasks

Composite tasks are constructed out of a number of constituent task (sub-task) instances. Sub-tasks are either primitive or composite tasks. A composite task is modelled as the parallel composition of its interfaces (input/output sets) and its constituent task instances. The data objects of a composite task's "external" interfaces are bound to data objects of its constituent tasks. Moreover, there may be notification dependencies between external and internal (sub-task) interfaces.

However, incoming notification dependencies to the composite's own input sets and outgoing notification dependencies from the composite's output sets are not known in this context. The aim is again to achieve reusability of the composite task model. This principle is captured in the specifications of the external input and output sets of composite tasks: an `InputSet` is an interface set with no input notifications and an `OutputSet` is an interface set with no output notifications.

```
|| InputSet (Objs=1, ONotfs=1) =
      if (Objs ==0 && ONotfs==0) then
         Iface_Problem
      else (Iface(Objs, 0, ONotfs)).

|| OutputSet (Objs=1, INotfs=1) =
      if (Objs ==0 && INotfs==0) then
         Iface_Problem
      else (Iface(Objs, INotfs, 0)).
```

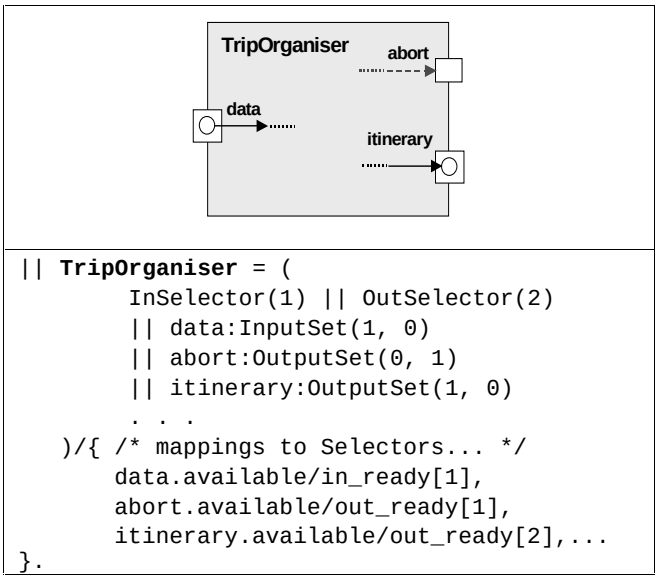
The conditional specification in the above model states that: 1) an external input set must have at least one data object or one outgoing notification; 2) an external output set must have at least one data object or at least one incoming notification. Process `Iface_Problem` is again used to model a transition to an error state, if either of the above conditions is not satisfied. For example, composite task `TripOrganiser` (of Figure 2) has one external input and two external output sets.

In the case of composite tasks, we have again to model the fact that exactly one input set is selected even if more than one is available and exactly one output set is enabled when the task terminates. The later is modelled by processes `InSelector` and `OutSelector`:

```
InSelector (InSets=1) =
   (in_ready[i:1..InSets] -> STOP).
OutSelector (OutSets=1)=
   (out_ready[i:1..OutSets] -> STOP).
```

These processes are used in the model of a composite task to guarantee single set selection, as shown in Figure 4. Unlike `AbsTaskImpl` (see section 3.2) these processes do not impose the causal dependency between a task's input and output sets. For a composite task, this dependency must be ensured by its internal implementation.

The main part of a composite task's model consists of the parallel composition of instances of its constituent tasks. For example, task `TripOrganiser` consists of instances of tasks `Planner`, `FlightSrch`, `CarRental` and `Reservation`. Within the context of a composite task, a task instance may need to receive and provide notifications to its environment. Respectively, each sub-task instance may need to be composed with processes of type `InNotification(ID)` or `OutNotification`, that apply to its interface sets. For example, `TripOrganiser` consists of the following processes:




```
|| TripOrganiser = (
        InSelector(1) || OutSelector(2)
        || data:InputSet(1, 0)
        || abort:OutputSet(0, 1)
        || itinerary:OutputSet(1, 0)
        . . .
   )/{ /* mappings to Selectors... */
       data.available/in_ready[1],
       abort.available/out_ready[1],
       itinerary.available/out_ready[2],...
}.
```

Figure 4. "External" input and output sets of a composite component.

```
|| TripOrganiser = ( . . .
     /* Constituent tasks ... */
     || plan:Planner
     || plan.abort:OutNotification
     || fs:FlightSrch
     || fs.abort:OutNotification
     || cr:CarRental
     || cr.abort:OutNotification
     || res:Reservation
     || res.abort:OutNotification
   ) / {  . . .  }.
```

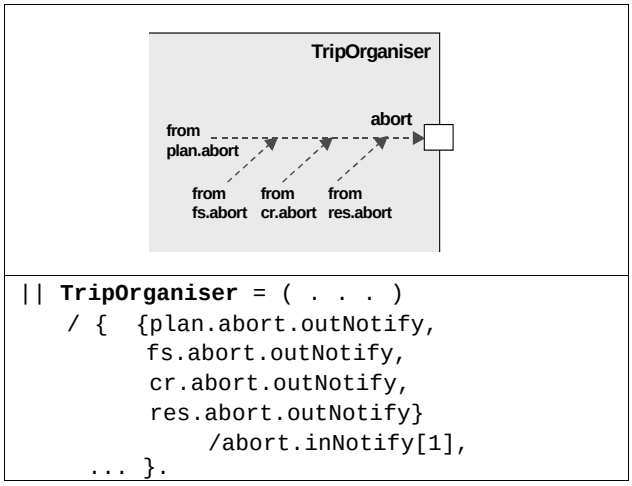
In this example, the `abort` output sets of all sub-tasks are sources for notification dependencies, in the context of `TripOrganiser`. The naming of a notification process ensures that its available action is synchronised with the available action of the corresponding interface set. So, both action `available` of interface `abort` for task `plan:Planner` and action `available` of process `plan.abort:OutNotification` are named `plan.abort.available`, and thus need to be executed synchronously.

Finally, we need to model the bindings (expressing both dataflow and notification dependencies) between interface sets of composite tasks. As discussed, bindings are modelled by means of appropriate re-labellings. For example, the following captures dataflow dependencies between external and internal interfaces for task `TripOrganiser`:

```
data.output[1]/plan.data.input[1],
itinerary.input[1]/res.booking.output[1],...
```

The following captures dataflow dependencies between internal interfaces for this task:

```
plan.details.output[1]/fs.details.input[1],
plan.details.output[2]/cr.details.input[1],
fs.flight.output[1]/res.details.input[1],
cr.car.output[1]/res.details.input[2], ...
```




```
|| TripOrganiser = ( . . . )
   / {  {plan.abort.outNotify,
         fs.abort.outNotify,
         cr.abort.outNotify,
         res.abort.outNotify}
              /abort.inNotify[1],
     ... }.
```

Figure 5. Modelling alternative input sources.

Note, that a given set or object may have more than one alternative input sources. Availability of *any* of the input sources (logical OR) is enough to enable the set or object, accordingly. Alternative dependency sources are modelled by means of *relational relabelling*. In our example, the `abort` output set of `TripOrganiser` can be enabled by a number of alternative sources: `plan.abort`, `fs.abort`, `cr.abort` and `res.abort`. The relational relabelling of Figure 5 states that a transition labelled `abort.inNotify[1]` in the LTS of the "external" output set `abort` is, now, performed when *any* of the other three transitions occurs. The corresponding transformation of the LTS is shown in Figure 6.

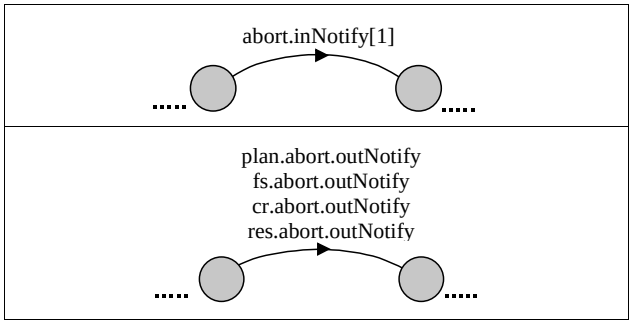


Figure 6. Relational relabelling used to model alternative input sources.

4. Workflow analysis

This section describes how to customise generic LTS analysis techniques for the domain of workflow systems.

4.1. Interactive simulation

A practical first step in checking a process is to simulate its behaviour. Simulation is performed as a user-controlled animation of the process. For composite processes, the LTS of their behaviour is not composed first. The LTSs of the components of the process are used to determine the current state of the process, as well as which actions are enabled at that state. The enabled actions are the "ticked" actions in the "animator window". When the user selects one of these actions, the process transits to the corresponding next state. The LTSA tool highlights the transitions on the LTS diagrams of the component processes and presents the corresponding system trace.

Figure 7 illustrates the interactive simulation of an instance of task `FlightSrch`. We can see that after the input to the task has been provided, its input set `details` becomes available. Action `details.available` is performed synchronously by processes `details: AbsInputSet(1)` and `AbsTaskImpl(1,2)`. Since this is a primitive task, the outputs become available, as soon as an input set is ready. In this case, when both actions `abort.available` and `flight.available` are activated, users may select which output to execute, according to the scenario they wish to check.

Interactive simulation provides an intuitive way for the system designers to experiment with different execution scenarios. However, in the general case, interactive simulation cannot establish the correctness of a real system, since designers cannot simulate all its possible execution scenarios. For that reason, techniques are required for rigorously checking the models of workflow systems.

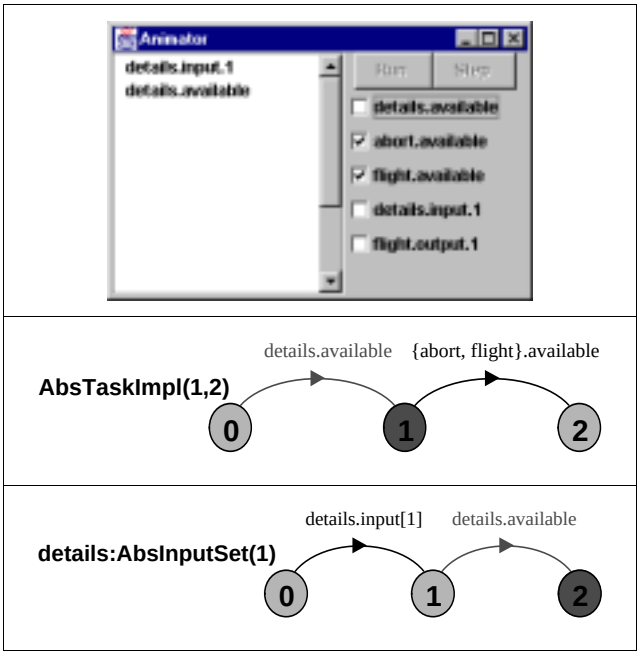


Figure 7. Interactive simulation of task `FlightSrch`.

4.2. Properties

The model-checking techniques associated with TRACTA can be used to check a workflow system exhaustively, against both generic and domain-specific properties. When a property is violated, our tools provide a *counter-example*, an execution trace that violates the property.

Generic safety properties: deadlock

LTSA identifies deadlock states in the LTS of a process, as states with no outgoing transitions. Reachability of such states is checked by default for every process in the system. This is so because LTSA has been mainly aimed at reactive models that exhibit non-terminating behaviours. A typical way of dealing with terminating executions is to add a looping transition to each valid terminating state of a system. For workflow tasks that are expected to terminate, we provide a generic process called `ValidTask-Termination`, which models the fact that a valid terminating state of a task is one where some output of the task has been enabled:

```
ValidTaskTermination = (out_enabled -> TERM),
TERM = (term_ok -> TERM).
```

When composed with a task that we wish to check for deadlock, this process will add looping transitions to the valid terminating states of the task. Thus, only real deadlock states will have no outgoing transitions in the resulting LTS.

```
|| Complete_TripOrganiser =
  ( TripOrganiser
    || organiser:ValidTaskTermination)
   /{ {abort.available,itinerary.available}
       /organiser.out_enabled}.
```

Here, an instance of `ValidTaskTermination` is composed with an instance of `TripOrganiser`. Relational relabelling is applied, so that the `ValidTaskTermination` process transits to its terminating state whenever *any one* of the outputs of `TripOrganiser` is enabled. Thus, valid terminating states of process `Complete_TripOrganiser` will have looping transitions labelled with action `organiser.term_ok`. Indeed, the LTSA tool does not detect any deadlocks in `Complete_TripOrganiser`:

```
States Composed: 76 Transitions: 136 in 0ms
          No deadlocks/errors
```

Assume that another version of the `Planner` was used in the definition of `TripOrganiser`, as depicted in Figure 2. In this case, `Planner` has two *alternative* output sets, one for a flight booking and another for a car booking; now, LTSA does detect a deadlock in process `Complete_TripOrganiser`, as shown in the trace below. Intuitively, the input set of the `Reservation` task will never be enabled because its two objects indirectly depend on the two alternative outputs of `Planner`.

```
Trace to DEADLOCK:
```

```
data.input.1
data.available
data.output.1
plan.data.available
plan.details1.available
plan.details1.output.1
fs.details.available
fs.flight.available
fs.flight.output.1
```

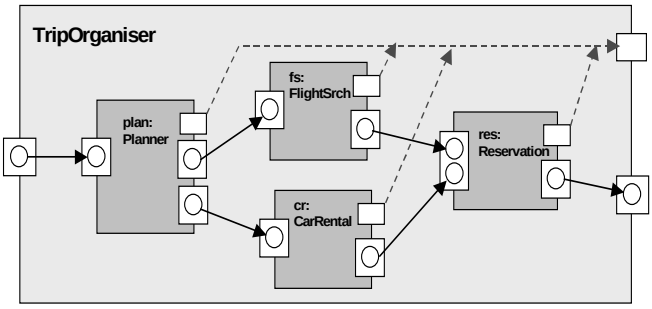


Figure 8. Composite task with deadlock.

According to our approach, the fact that a task has no deadlocks implies that it eventually terminates. Therefore, checking safety in terms of absence of deadlock also guarantees the main liveness property of termination, which is of interest in this context. Specific liveness-checking techniques are required [14], when the behaviour model of the resources used for the execution of each primitive task is also introduced in the system model. The analysis of workflow schemas, in the presence of resource models, is an ongoing research issue as discussed in section 5.

Other generic safety properties

In TRACTA, safety property violations are identified by the reachability of a special "error state", represented as state -1 in LTSs. The error state has special semantics [13]. First, it has no outgoing transitions; there is no meaning in exploring a system after a safety violation has occurred. Moreover, in the context of parallel composition, local errors are propagated globally. That is, if any component of a global state is an error state, then this global state is also an error state. Safety properties are specified as FSP primitive processes, whose definition is prefixed with the keyword "property". A fundamental requirement to be satisfied by all composite tasks is:

- *The output produced by a task causally depends on the input that triggers the task execution.*

It is expressed by means of a safety property:

```
property Task_InOut_Relation =
    ( input_ready -> output_enable -> STOP ).
```

This property has an alphabet of two actions: `{input_ready, output_enable}`. It asserts that action `output_enable` can occur only after `input_ready` and none of these actions is allowed to occur again. In the corresponding LTS, any trace from the property's alphabet that does not satisfy the property leads to the error state. Property process `Task_InOut_Relation` is composed with process `Complete_TripOrganiser` in order to check for potential violations of the property in the non-blocking version of this task. Figure 9 illustrates the LTS for property `Task_InOut_Relation`, after relational relabelling is applied. It specifies, that if *any* one of the input sets (just `data` in our example) is enabled, then (and only then) *any* one of the output sets may be enabled by the corresponding task.

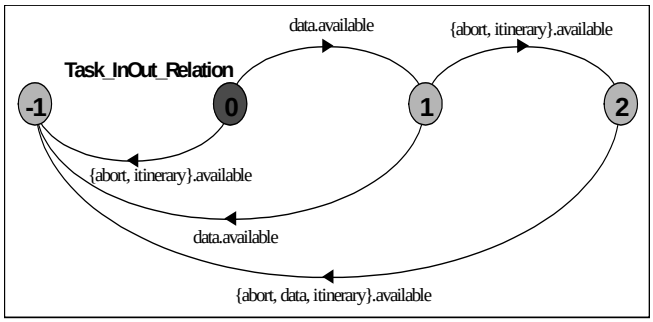


Figure 9. LTS of property Task_InOut_Relation.

```
|| Check_InOut_TripOrganiser =
       ( Complete_TripOrganiser
       || Task_InOut_Relation )
   / { data.available / input_ready,
       {abort.available, itinerary.available}
          / output_enable }.
```

Another typical requirement for any workflow schema is:

- *For each task, there must exist at least one execution of the workflow where this task is triggered.*

To check this for some task `T`, we introduce a property `PathsToSubtask` to the model, which states that no input set of T ever becomes ready. If LTSA returns a counterexample, it means that indeed, there exists some execution where `T` is triggered, as desired. If LTSA detects no violations, it means that `T` never plays any role in the context of the specific workflow.

```
property PathsToSubtask = STOP + {reachable}.
```

Here, action `reachable` (explicitly added to the alphabet of the property) expresses the fact that a task is triggered. In the case of a task, `reachable` is relationally relabelled to the set of `ready` actions corresponding to the task's input sets. For example, we proceed as follows to check that task `res:Reservation` is triggered in at least one execution of `Complete_TripOrganiser`:

```
|| ExistPathsToPlan =
   (Complete_TripOrganiser || PathsToSubtask)
   / {res.details.available/reachable}.
```

The LTSA tool returns the following result:

```
Trace to property violation in
PathsToSubtask:
       data.input.1
       data.ready
       data.output.1
       plan.data.ready
```

The counterexample gives the prefix of an execution of `Complete_TripOrganiser` where task `res:Reservation` is triggered.

Domain-specific safety properties

In addition to checking generic properties of workflows, our techniques can be used for properties that refer to the particular workflow under analysis. Examples of such properties include checking that: a certain sub-task is triggered only after a number of other tasks are executed in a specific order; if any sub-tasks aborts, then the only possible outcome of the composite task is also abort; no sub-task is triggered subsequently to any abort action in the composite task. A detailed discussion of domain-specific safety properties as well as liveness properties can be found in [15].

4.3. Modularity and Abstraction

After checking thoroughly that a task satisfies its requirements, the behaviour of the task may be abstracted before re-using it in some other context. The only actions that need to be visible by the context of a task are actions related to its interfaces. Specifically, the interface of an abstracted task consists of the `input` actions of its input sets and the `output` actions of its output sets. The `available` actions of input sets and output sets must also be exposed, in order to be able to add notifications to and from the task when it is introduced in a context. The LTS of the task is then minimised. For example, the `Complete_ TripOrganiser` task is abstracted as follows. Minimisation reduces the size of the LTS of the reservation task from 76 down to 9 states.

```
minimal
|| AbstractTripOrganiser =
   (TripOrganiser )
      @ { data, abort, itinerary }.
```

5. Discussion and conclusions

The paper has proposed the modelling of workflow schemas (using a popular notation) by means of Labelled Transition Systems, as they are supported by the TRACTA approach. TRACTA satisfies the fundamental requirements that have been set in section 2.2. It is a mature method that has been extensively used for model checking of complex concurrent and distributed systems. It uses a solid automata-based theory to allow exhaustive analysis on the static model of a system, at design time.

The TRACTA approach is fully automated within the LTSA toolkit. The algorithms employed for process composition, action hiding and minimisation are computationally efficient and scale well for real-world workflow schemas. In addition, LTSA provides a graphical representation of LTSs and an animation facility for simulating the execution of the model. Diagnostic information is presented in the form of counterexamples: traces of execution that lead to violation of a desired property. All these facilitate the use of the method by designers that are not experts in formal methods. In fact, with an automated production of the model from the workflow schema definition (which is currently under development), the workflow designers will not have to write any FSP code. Generic properties could also be provided as predefined options. Therefore, designers would only need to express additional application-specific properties that they may wish to analyse.

Our plans also involve facilitating the understanding of the counterexamples returned by the LTSA tool, by providing designers with custom animations on graphical displays of the workflows. We have already experimented extensively with domain-specific animations, and intend to apply our experience to workflows [16].

The feature of TRACTA that makes it particularly suitable for behaviour analysis of workflow schemas is *compositionality*. TRACTA traditionally follows a compositional approach to modelling and analysis, in order to address the state explosion problem, which is inherent to all exhaustive reachability analysis techniques. We have exploited this feature, by making the models of tasks context independent and re-usable. Therefore, designers can check the model of their system in an incremental manner, while the system is designed. Design errors can be spotted early in the design and right in the components (tasks) where they occur.

The lack of compositionality is the main weakness of the *Woflan* system, according to its designers [17]. Woflan is a verification tool that uses a special type of Petri-nets to model and analyse the behaviour of workflow processes. Errors in the model are reported in the form of "behaviour error messages", similar to our "counter-example traces". The main advantage of the system is the theoretical robustness of the Petri-nets and the clear representation of workflow state by token-based nets. However, the system lacks a means for visual representation of the model. In addition, Woflan can only handle systems with just up to 10^5 states. LTSA can handle LTSs with more than 10^6 states. Such LTSs typically represent systems that are originally several orders of magnitude larger (before minimisation is applied during the various levels of composition).

Another approach for workflow verification has been proposed by the *Praxis* project [18]. However, they focus on graph analysis techniques to identify structural conflicts in workflow schemas. The approach is bound to a specific

workflow notation and depends on special-purpose elements in the notation (and-split, or-split, etc). It does not cater for analysis against general safety properties and cannot be easily adapted to other workflow notations.

There are a number of directions we are planning to follow in order to extend the work presented in this paper. The proposed modelling approach has been illustrated by means of a specific workflow notation. This notation is part of a proposal to OMG's "UML Profile for EDOC" RFP [9]. In any case, the mapping is generic and can be easily adapted for other approaches to workflow scheme specification. To justify this claim, we are planning mappings for other (proprietary) notations used by commercial workflow management systems. In addition, the proposed mapping has to be extended with a generic model of recursive tasks (tasks that can trigger new instances of their own type), a common pattern in business processes.

This paper introduces an approach for modelling and analysis of workflow schemas, irrespectively of the environment in which schemas are instantiated and executed. Such models can be enriched with the behaviour of system resources used for the enactment of workflow instances. Analysis of the extended models can then ensure that workflow specifications are consistent with the constraints set by the execution environment. We are currently investigating what are the required abstractions for modelling system resources in this setting.

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